Unlimited

YAGER MARS LANDER RECONTAMINATION:

STATUS OF PRELIMINARY STUDIES

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VOYAGER MARS LANDER RECONTAMINATION:

STATUS OF PRELIMINARY STUDIES

OF SELECTED EFFECTS

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SUMMARY

OBJECTIVES

1. Describe the mechanisms which could conceivably act to biologically contaminate the Voyager entry vehicle during and after biobarrier opening.

2. Evaluate each mechanism and rank in order of importance.

3. Estimate the degree of biological recontamination due to each mechanism and combine these to determine the amount of recontamination for each separation sequence.

4. Draw conclusions and make recommendations relative to the design and operations which may reduce the recontamination probability.

RESULTS AND CONCLUSIONS

1. The order of importance of the effects considered in this report is as follows:

   Evaporative streaming

   Electrical forces at separation of biobarrier and lander

   Attitude control gas, particularly reflection from the inside of the biobarrier in conjunction with biobarrier removal

   Random walk of macroscopic particles carrying viable organisms over the spacecraft surface (due to spacecraft vibration)

   Meteoroid effects (kick-off)

   Attitude control gas: turning of macroscopic particles around surface edges

   Orbit insertion and trim motor burning causing particles to move opposite to the main flow

   Pressurized gas in the biobarrier

2. The study has shown that the requirement of no line-of-sight path from the lander to any unsterile part of the spacecraft should include, as well, that no reflections from the biobarrier can result in line-of-sight paths. This favors a biobarrier which opens and shields the lander from the bus.

3. Atomic and molecular clouds of material evaporated from the surfaces of the lander are an important environmental factor in the assessment of the ability of macroscopic particles to attach to the lander.

4. Electrical forces are most important as a recontamination mechanism during the early phases of separation of the biobarrier and of the lander.

5. No electrical mechanism has been identified which acts to contaminate the lander during the period from after biobarrier separation until the lander begins to separate.

6. Asymmetrical removal of the biobarrier and the simultaneous firing of an attitude control gas jet (which the tip-off torque causes) is an important potential recontamination mechanism.

7. Based on preliminary information, after the biobarrier is opened the turning of macroscopic material in jet plumes around surface edges will not occur after the flow moves about ten nozzle-exit diameters from the nozzle.

8. Movement of material over the surface of the spacecraft in which macroscopic particles leave and return to the surface will be influenced by the evaporative effect of surface materials with high vapor pressure or high rates of decomposition.

9. The effect of meteoroids is to reduce the number of viable organisms on the surface and to introduce some of them into the cloud of particles around the spacecraft.

10. Most of the material in the boundary layer and a very small amount of material in the free-stream flow of the orbit insertion and trim motors can move in the direction opposite to the main flow and impinge on the spacecraft. Because of the low density of this flow it will be unlikely to turn macroscopic particles around a surface to contact the lander.

11. Pressurized gas within the biobarrier can, at the moment of biobarrier separation, be a potential recontamination mechanism.

RECOMMENDATIONS

1. No line-of-sight paths, including reflection from the sterile inner part of the biobarrier during its separation, should be allowed from any unsterile part of the bus to the lander.

2. Further study of the effect of evaporative streaming from materials to inhibit attachment of macroscopic particles to the lander should be carried out. This should include an evaluation of the utility and practicality of purposely introducing material on the lander or inside the biobarrier to enhance the streaming of atoms or molecules away from the lander.

3. A study of the ability of jets in the space environment to turn macroscopic particles around surface edges should be carried out to confirm the preliminary conclusion that this does not occur.

4. A study of the flow of boundary layer material from the orbit insertion and trim motors in a direction opposite to the main flow should be conducted.

5. If pressurized gas within the biobarrier is a requirement it should be vented before separation of the biobarrier occurs.

6. A system analysis of the recontamination probability of each candidate separation sequence should be carried out after more definitive analysis has established the probability distribution of recontamination caused by each mechanism within a sequence.

SECTION 1

INTRODUCTION

A constraint placed upon the design and operation of the Voyager mission requires that the probability of biological contamination of Mars be less than a very low value as the result of a single mission until a specified number of years have elapsed. This report treats selected aspects of this general problem related to lander recontamination.

Recontamination of the Voyager lander can occur in-flight during and after bio-barrier removal in the vicinity of Mars. The purpose of this report is to describe and analyze several of the possible mechanisms which can cause recontamination. Each mechanism is described in terms of the source of the viable material on or near the spacecraft and the way this material is moved to the lander. Analysis then proceeds to evaluate the importance of selected mechanisms. A ranking of each in terms of its importance is carried out in accordance with the results of this analysis.

In general, recontamination of the lander prior to the first phases of biobarrier removal is not included in this analysis. For example, recontamination of the lander by meteoroid puncture of the biobarrier is not considered here. Also the biological burden of the spacecraft up to the point of separation of the bio-barrier is not directly studied--it is considered as an input to this study. Some work bearing on this question is, however, included in Section 5 under Effect of Meteoroids. Similarly, no attempt has been made to determine the relative importance of pyrotechnics on the lander recontamination problem.

During the course of the work it was discovered that the effect of evaporation of material from the surface of the spacecraft could produce forces on macroscopic particles which under certain conditions could be as large or larger than those previously considered; e.g., electrical or solar radiation pressure forces.

Because of this, some of the effort of the study was diverted to include assessment of this effect and to include, in the Appendix, information which was readily available to the author as the result of work on other contracts at TEMPO.

Many of the mechanisms are analyzed to determine a reasonable upper limit to the effect considered. Because only limited data and theory are available to determine better evaluations of the importance of each effect, considerably more basic work is required, both theoretically and experimentally.

The author wishes to acknowledge the assistance obtained from R. P. Wolfson, J. H. Chestek, and M. J. Concannon of the Pasadena Engineering Office, Advanced Planetary Programs, General Electric Company and from G. E. Ingram of TEMPO. Michael Concannon contributed, in addition to consultation on design aspects of the problem, by preparation of the illustrations in this report.

SECTION 2

STATEMENT OF THE PROBLEM

The central problem in a study of lander recontamination is to evaluate potential mechanisms which can cause viable organisms to move to the lander during and after biobarrier removal. Experimental evidence and data on the transport of material carrying these biological materials in the space environment is not available. It is only possible to approach the problem by use of simple physical concepts and intuition at the present time. An important part of the problem solution is to provide a framework from which more accurate and definitive investigations can proceed. Some of these additional studies are described briefly in the recommendations.

The problem has been limited to a selected set of mechanisms which, in the view of the author, are the most important and are subject to some kind of reasonable upper-limit evaluation at the present time.

Therefore, the mechanisms considered are not necessarily the only ones which can cause transport of material to the lander. The mechanisms considered are evaporative streaming, electrical forces, attitude control jet and motor burning effects, motion of particles on the surface, meteoroid effects, and pressurized gas within the biobarrier. Two effects have been purposely excluded from the investigation: meteoroid puncture of the biobarrier and the effect of pyrotechnics. The meteoroid problem is being studied under related efforts and pyrotechnics of an enclosed type can be used.

In addition to evaluating each of the selected effects, an important part of the problem is to develop, from a systems viewpoint, the combined evaluation of the mechanisms for each candidate separation sequence. This part of the problem has only been examined in a cursory way because some of the effort on this study was diverted to an investigation of evaporative effects. It is also felt that more refined quantitative estimates are required before the results can be probabilistically combined in a meaningful way to give the probability distribution of viable organisms on the lander. Related to this, of course, is the requirement for better knowledge of the biological burden on and in the spacecraft. This information is being accumulated as the result of other studies to aid in the approach to the problem from the systems point of view.

SECTION 3

CAPSULE SEPARATION SEQUENCES

Three different separation sequences were considered to define the events and mechanisms which can cause transport of viable organisms to the lander (Ref. 1).

1. Biobarrier separation prior to orbit injection (as in Task B)
2. Biobarrier separation in Mars orbit
3. Biobarrier opened in Mars orbit, but remaining with spacecraft

The events that can cause recontamination and occur as a result of these sequences are as follows.

Sequence 1:

Biobarrier separation

Attitude control gas firing during and after separation of biobarrier

Vibration

TVC pressure squib firing

Orbit insertion motor burn when lander exposed

Orbit trim motor burn when lander exposed (if required)

Pitch and yaw turns with attendant firing of attitude control jets

PSP deployed and moved to preplanned position

Lander separation

Attitude control jet firing (if tip-off torque sufficiently high)

Sequence 2:

Biobarrier thrusting (two burns may be required to lower probability of collision of biobarrier and bus)

Attitude control jets firing (if biobarrier tip-off torque sufficiently high)

Vibration

Lander separation

Attitude control jets firing (if lander tip-off torque sufficiently high)

Sequence 3:

Biobarrier opening

Vibration

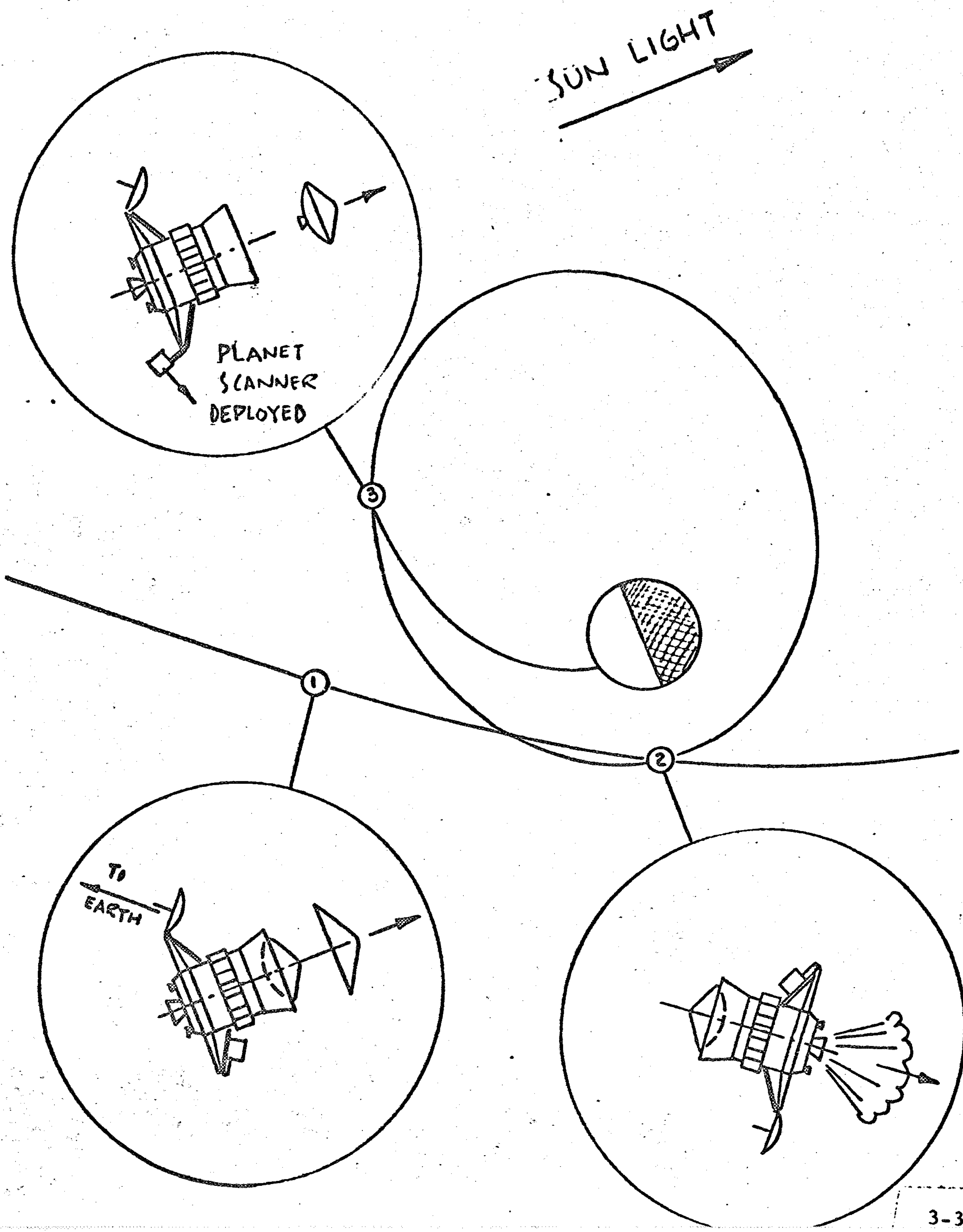
Lander separation

Attitude control jets firing (if lander tip-off torque sufficiently high)

Sequence 3 appears to have less events at the level of detail considered above that can cause recontamination. In addition, it probably provides the least time from biobarrier removal to lander separation although this time can be made very short in Sequence 2 as well. These sequences are illustrated in Figures 3-1, 3-2, and 3-3.

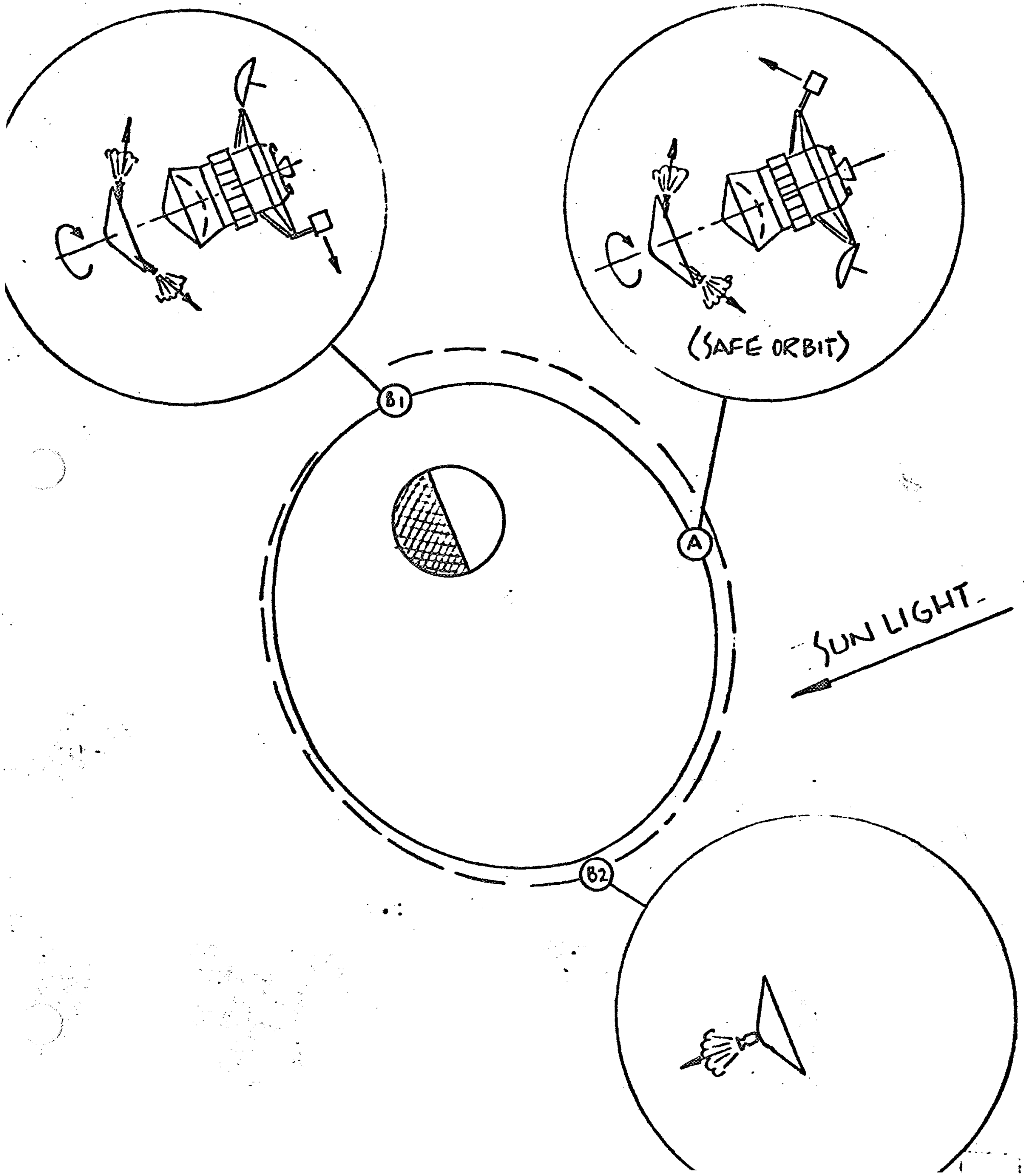
CASE I - CANISTER SEPARATED PRIOR TO ORBIT INSERTION

Figure 3-1. Illustrating Sequence 1.



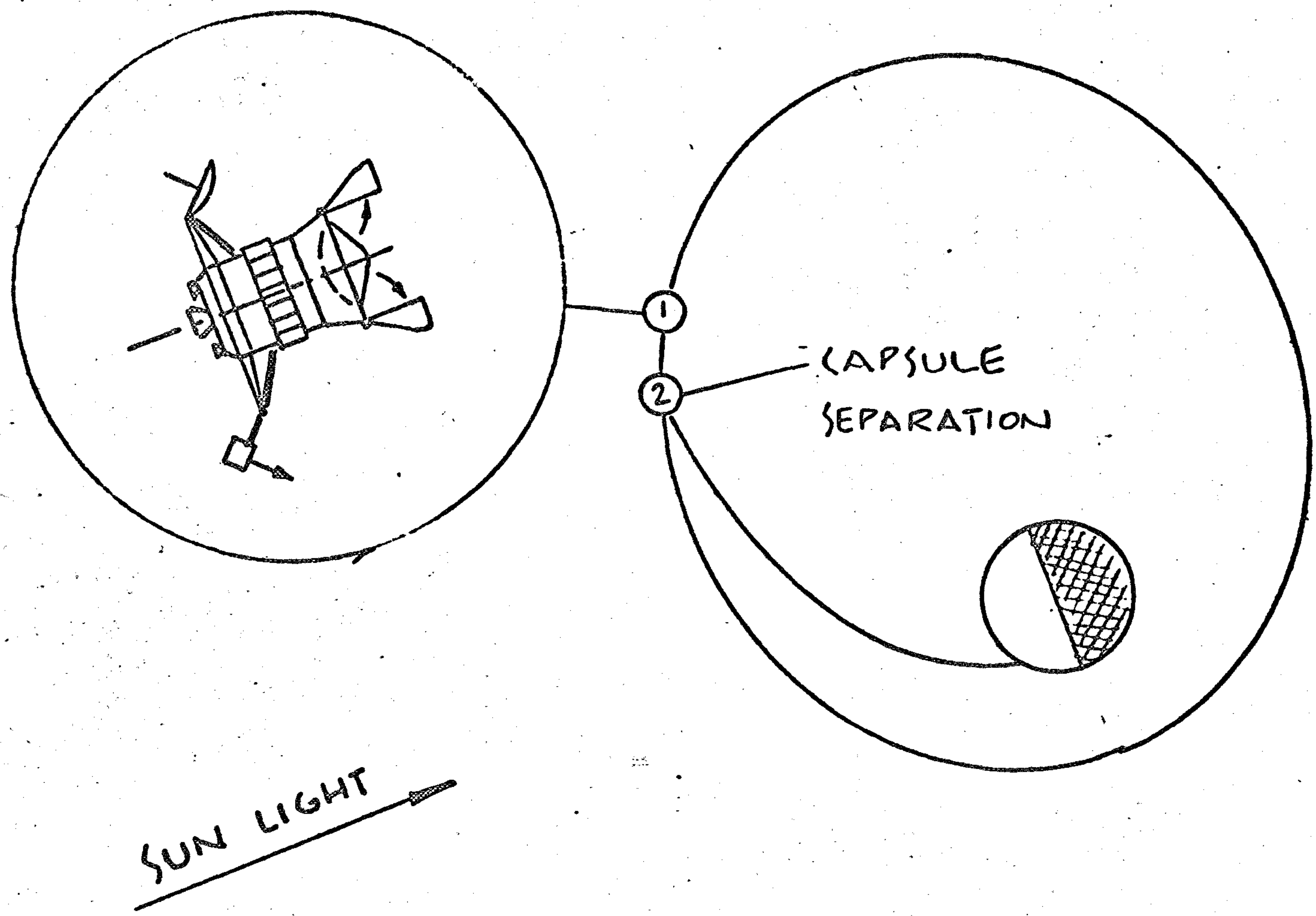
CASE 2 -
NISTER SEPARATED IN MARS ORBIT - OPTIONS A & B

Figure 3-2. Illustrating Sequence 2.



CASE 3 -
CANISTER HINGED ON SPACECRAFT

Figure 3-3. Illustrating Sequence 3.



SECTION 4

ATOMIC AND MOLECULAR CLOUDS AROUND SPACECRAFT

Evaporation, decomposition, and outgassing of materials of the spacecraft can cause a streaming of atoms and molecules away from the spacecraft. There is evidence from Gemini wake studies and the optical environment of spacecraft (Ref. 2) that such a cloud may exist.

4.1 ESTIMATES OF THE FORCE ON MACROSCOPIC PARTICLES DUE TO EVAPORATIVE STREAMING

The material in the appendix serves as a starting point for the evaluation of the force on a particle near a surface due to collisions with atoms or molecules leaving the surface.

The approximate value of the force on a macroscopic particle is given by

$$F = pA \tag{4-1}$$

where

p = equivalent pressure caused by the streaming particles

A = projected area of particle

Equation (8-6) in the appendix provides the number density of these particles near a metallic surface of the spacecraft.

The pressure (dynes cm^{-2}) may be found from

$$p = A\rho_v kT \tag{4-2}$$

where

ρ_v = number density of particles streaming from the surface (cm^{-3})

k = Boltzmann constant (1.38×10^{-16} erg/°K)

T = temperature of surface (°K)

The following table shows the estimated force on a test particle 4 mils in radius ($A = 7.8 \times 10^{-6}\ cm^2$) over surfaces at several temperatures and consisting of several different materials.

Table 4-1. Force on a small particle due to Evaporative streaming

Material	Surface Temperature (°K)	Force on 4-mil particle	
		dynes	lbs
Al	900	2.0×10^{-8}	4.5×10^{-14}
Al	600	1.3×10^{-14}	2.9×10^{-20}
Al	300	6.0×10^{-19}	1.35×10^{-24}
Cs	300	7.0×10^{-7}	1.58×10^{-12}
Mg	1000	2.2	4.95×10^{-6}
Mg	490	1.5×10^{-7}	3.38×10^{-13}
Zn	300	6.0×10^{-12}	1.35×10^{-17}
Phenolic refrasil	300	9.75×10^{-12}	2.2×10^{-17}

The electrical force (Ref. 3) within a few Debye lengths of the surface is expected to be on the order of 10^{-14} lbs. For some materials the force caused by streaming will be of the same order of magnitude or even higher than the electrical forces.

The effective range of this force is short because the density of particles drops off rapidly due to geometric spreading. The principal effect of the force is to reduce the probability of particles attaching to the lander if they are simply drifting as a cloud around the vehicle.

The velocity imparted to a 4-mil test particle over Cs due to this streaming effect is likely to be the largest which can reasonably be expected. This velocity is imparted to the particle while it is close to the surface. To estimate this velocity, assume the density of evaporated particles is 10^{12} cm^{-3} at the surface and drops off with the inverse square of the distance from the center of the vehicle. The vehicle equivalent radius is R. The force in dynes cm^{-2} is

$$F = A \rho_v k T \frac{R^2}{r^2} \tag{4-3}$$

where

r = distance from the evaporating surface

The energy imparted is equal to the energy gained:

$$\int_R^{\infty} F\,dr = \frac{1}{2} mv^2 \tag{4-4}$$

where

m = mass of test particle (g)

v = velocity of particle (cm/sec)

This yields

$$v = \sqrt{\frac{2A\rho v_o\, k\, TR}{m}} \tag{4-5}$$

Let

A = 7.8×10^{-6} cm^2 (4-mil particle)

ρ_v = 10^{12} cm^{-3}

T = 300°K

$R = 4$ meters

$m = 3 \times 10^{-5}$ gr (4-mil steel particle)

This yields a velocity of

$$v = 2.9 \text{ cm/sec} \tag{4-6}$$

Further investigation of the effect of purposely coating the lander with a layer of high vapor pressure material to prevent drifting particles from attaching to the surface is recommended.

SECTION 5

RECONTAMINATION MECHANISMS

Six different effects are described in this section which can potentially play a role in transporting biologically active material to the lander during and after biobarrier removal.

5.1 ELECTROSTATIC EFFECTS

In Reference 3 an estimate of the effect of electrical forces was carried out and it was concluded that the effect was too small to cause deorbiting of particles. It was also concluded that after the lander is exposed to the space environment and remains electrically connected to the bus there are negligible electrical effects which could directly transport particles to the lander from other parts of the spacecraft. This conclusion is supported by the study documented in this report. However, during the early phases of biobarrier and lander separation there is the possibility (depending on the importance of the photo-electric effect in charging the vehicles and the orientation of the vehicle with respect to the sun) that the biobarrier or the lander can become charged opposite to the bus. Figure 5-1 shows the relationship of the biobarrier to the other parts of the vehicle at the moment of biobarrier separation. If the orientation of the vehicle is such that sunlight falls unevenly on the two separated parts; e.g., if the biobarrier is in the shade, then it is possible for the two separating parts to be oppositely charged. The same effect can occur when the lander is separated (Figure 5-2). The rate of charging at the instant of separation is sufficiently high (Ref. 3) that is is possible to rapidly charge the part in the shade to a negative potential due to differential collision rates of ions and electrons while the part in the sun remains positively charged.

The maximum reasonable potential difference which is expected is about 20 volts. This potential can be dropped across a gap of a few centimeters and can give rise to electric fields much higher than those surrounding the vehicle when separation is not occurring. For example, an electric field of about 20/.10 =

Figure 5-1. Electrical Effects During the First Phase of Biobarrier Separation.

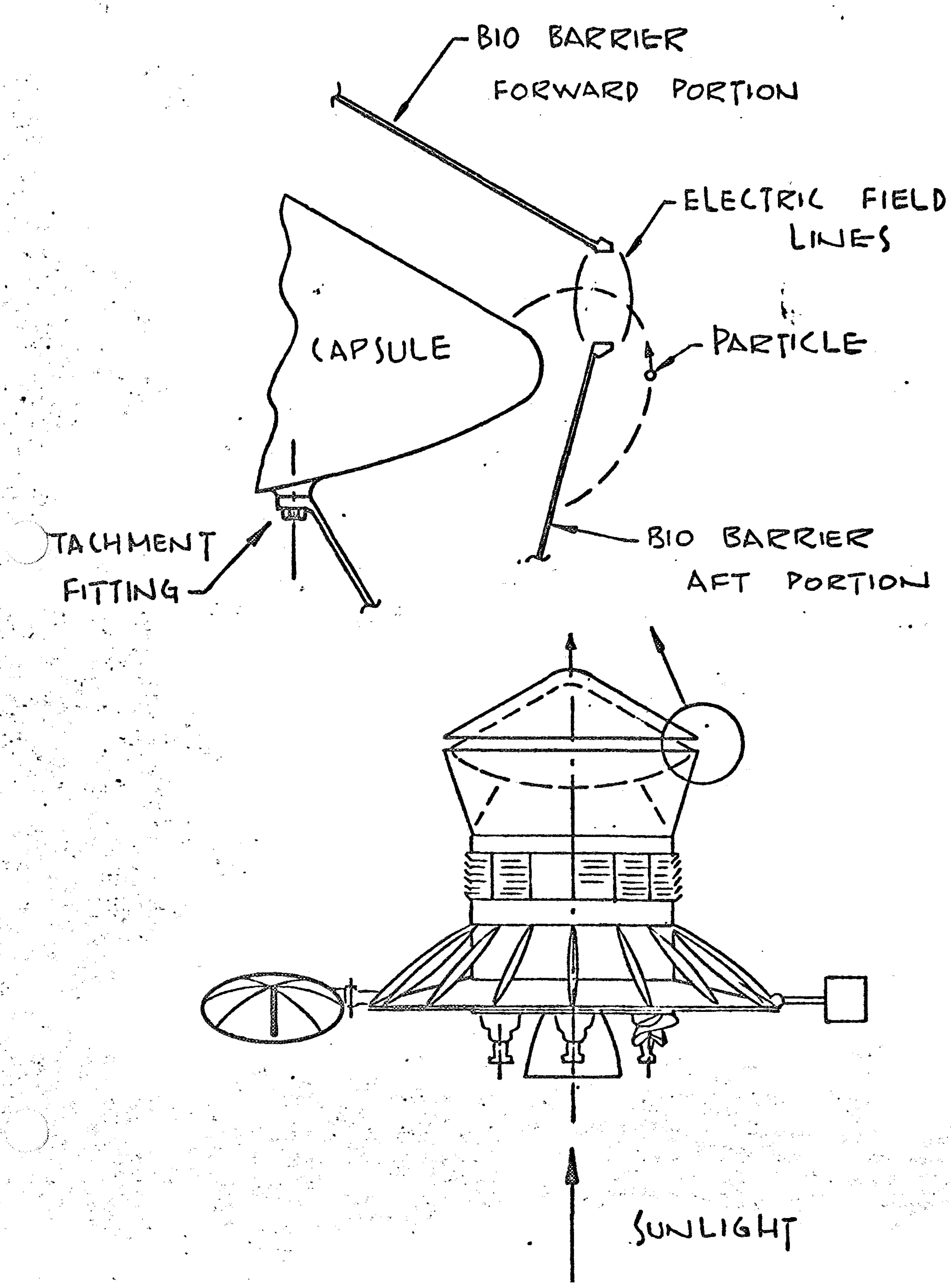


Figure 5-2. Electrical Effects During the First Phase of Lander Separation

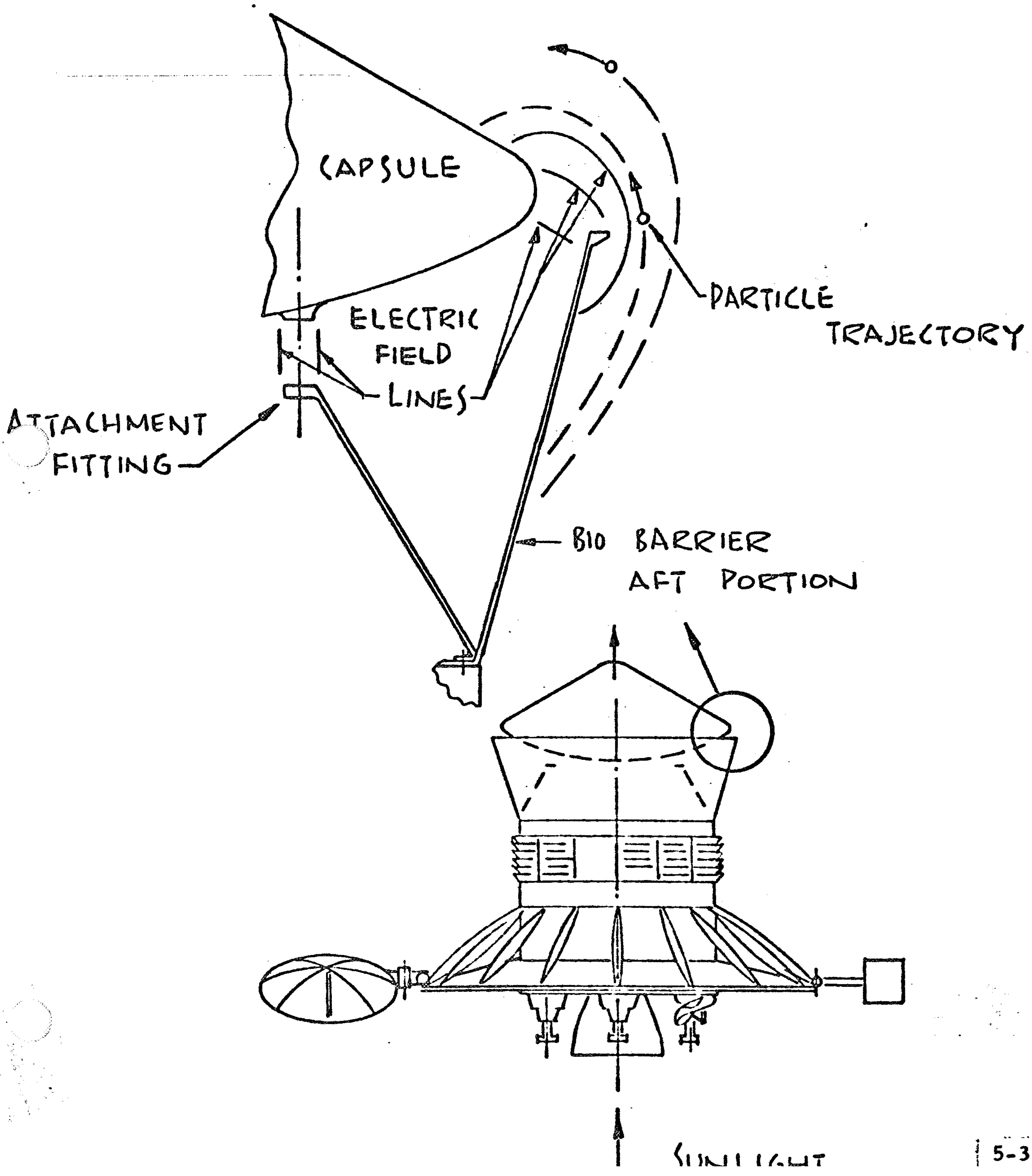


Figure 5-3. Reflection of Attitude Control Gas from the Biobarrier.

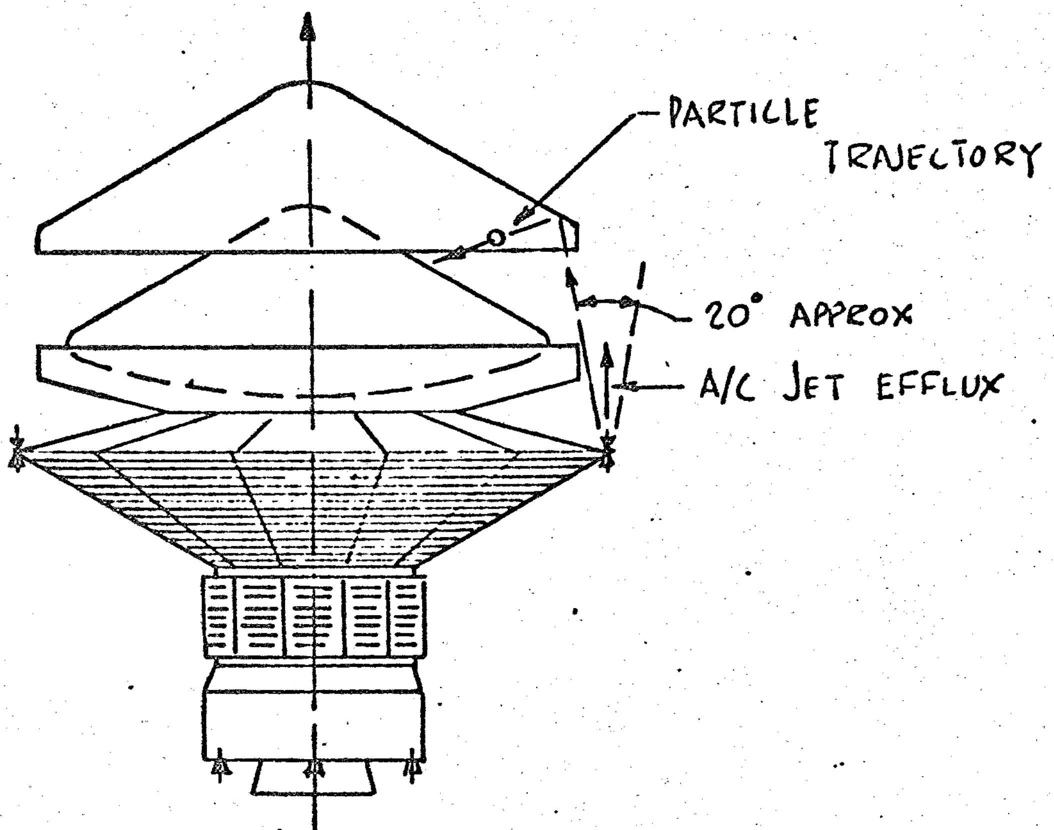


FIG. 4A SYMMETRICAL
BIO BARRIER SEPARATION
(HIGH TRUSS CONFIGURATION)

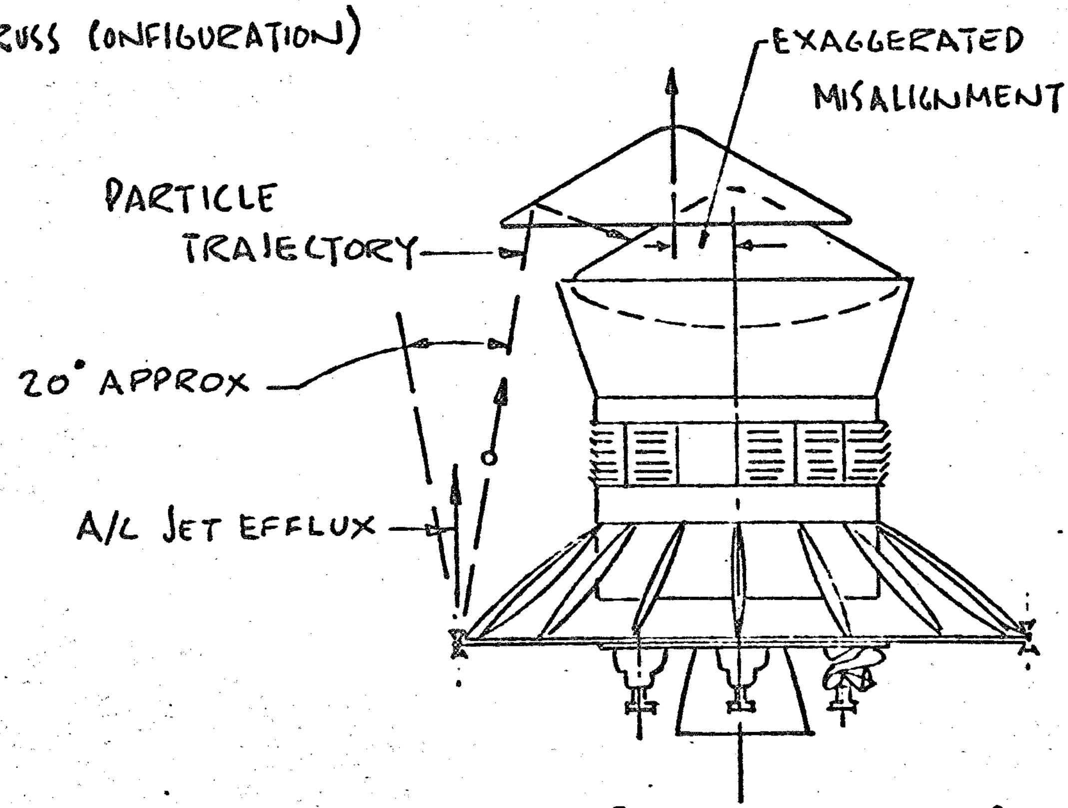


FIG 4B ASSYMMETRICAL BIO-
BARRIER SEPARATION (LOW TRUSS

200 volts/meter can occur across a 10-cm gap if flat plate geometry is assumed. Because the surfaces which are separating are irregular and may have high curvature, the fields developed could be a few orders of magnitude higher, say about 10^4 volts/meter.

The force on the test particle of Reference 3 is given by

$$F = QE \text{ newtons} \tag{5-1}$$

where

E = electric field strength (volts/meter)

Q = charge on particle (coulombs)

The following table shows the range of the value of this force in pounds for upper and lower limits of field strength and charge on the test particle.

Table 5-1. Force on a charged particle in pounds

Particle Charge (Coulombs) (Ref. 3)	Electric Field (v/m)	
	200	10^4
4×10^{-15}	1.7×10^{-13}	8.6×10^{-12}
4×10^{-11}	1.7×10^{-9}	8.6×10^{-8}

A force of 10^{-9} lbs will result in an acceleration of about 15 cm/sec^2 for the 4-mil steel test particle. When the biobarrier separates, particles can move to the lander under the influence of the electric field between the biobarrier and the bus. Similarly, when the lander separates, material can move from the unsterile parts of the bus to the lander under the influence of the electric field between the lander and the bus.

To aid in avoiding the possibility that the separating bodies can produce fields which recontaminate the lander the following can be investigated:

a. Allow as large a separation distance between the lander and the unsterile parts of the bus as is practical during separation of the lander.

b. Prevent different signs of charge on the separating parts by allowing sunlight to shine on each during separation.

c. Connect the separating parts by a wire until they are separated by a meter or two to prevent the occurrence of high electric fields.

d. Separate biobarrier and lander as rapidly as possible consistent with other system requirements.

5.2 ATTITUDE CONTROL GAS

Jets which provide attitude control by reaction can be a source of recontamination if any one of the following occurs.

a. The attitude control gas sweeps particles from the bus surfaces and deposits them on the lander. This can be a source of recontamination even if the attitude control gas is sterile.

b. The gas is not sterile and particles can turn around corners to impact the lander.

c. The gas is not sterile and reflects from the inner side of the biobarrier during its separation.

There is reason to believe (Ref. 4) that when the jets have expanded to a point about ten nozzle-exit diameters downstream, the gas does not have the capability to turn macroscopic particles around the corners of surfaces to impact the lander. The collision frequency in the gas will be too low to sustain a shock off the surface. The flow itself is not likely to turn and any particles in the flow are less likely to be turned by it.

The gas can reflect from the inner part of the biobarrier if there is a line-of-sight path (including reflection) from the nozzle to the lander. This is a potentially important kind of recontamination mechanism, particularly if the biobarrier separates slightly unsymmetrically about the axis of the spacecraft.

The reaction on the remainder of the vehicle is in a direction to cause the firing of the jet most likely to recontaminate the lander by reflection. This is illustrated in Figure 5-3 where the configuration is shown during biobarrier separation for two different types of spacecraft configuration.

It is recommended, in addition to a requirement for no line-of-sight path to the lander, that no paths which include reflection from the biobarrier be allowed. This additional requirement can be too restrictive under some conditions and probably should be limited to a time while the biobarrier is within a specified distance of the spacecraft.

5.3 RANDOM WALK OF MATERIAL ON THE SPACECRAFT SURFACE

After the biobarrier is opened the lander is exposed to the movement of particles along the surface of the spacecraft from the unsterile parts of the vehicle to the lander. The problem can be approached by considering the particles to move in a random walk from the unsterile parts across a region of sterile surface (within the biobarrier before it separates) to the lander. The frequency of steps can be taken as that caused by small meteoroids or dust (see Part 5.4) impacting the spacecraft or to the frequency of vibration due to the firing of the altitude control jets, orbit insertion or orbit trim motors. It is also possible that the vibration of the magnetometer boom or other structures could be a source of excitation of the particles.

Consider a one-dimensional random walk of a set of particles along the x axis. The close relationship of a random walk of particles to diffusion theory will be used. In Reference 5 it is shown that the probability that a particle is between x_0 and x_1 starting at $x = 0$ at time t,, is given by

$$P = (2\pi)^{-1/2} \int_{y_0}^{y_1} e^{-\lambda^2/2} d\lambda \qquad (5\text{-}2)$$

where

$$y_0 = (x_1 - 2ct)/\sqrt{2Dt}$$

$$y_1 = (x_0 - 2ct)/\sqrt{2Dt}$$

The quantity c is called the drift. It will be taken as zero here. However, we have reason to believe that the random walk will by unsymmetrical when the orbit insertion and orbit trim motors are burning because of the acceleration imparted to the vehicle which may not be shared by the particles. This effect is generally to move particles away from the lander. The quantity D is analogous to the diffusion coefficient in continuous movement and is given by

$$D = \frac{(\Delta x)^2}{\Delta t} \qquad (5\text{-}3)$$

where

Δx = step size of the particles

Δt = time required for each step

The step size depends on the degree of excitation of the surface. The time between steps can be taken equal to the period of the vibration. For example, for a frequency of 50 cps and a step size of 0.1 cm, the quantity D is 0.5 $cm^2\ sec^{-1}$. For a frequency of 1000 cps and a step size of 0.01 cm,

$D = 0.1\ cm^2\ sec^{-1}$. As the frequency increases it is expected that the step size will decrease because the excitation is less at higher frequency. There is, therefore, a range of reasonable values of D which probably extends from 10^{-2} to 10^{2}. It is possible to evaluate the quantity P when D varies over this range. The length $\sqrt{2Dt}$ is the controlling variable. When it is small compared with the dimensions of the bus, the probability of recontaminating the lander is small. When it is large compared to bus linear dimensions, the probability of contamination is large. An estimate of bus size is about L = 2 meters. Over the range of values of D, given above for times of 1 to 10^6 seconds, values can be constructed of the ratio $L/\sqrt{2Dt}$ as shown in the following table.

Table 5-2. Values of $L/\sqrt{2Dt}$ for several times and diffusion coefficient values.

Time (sec)	Diffusion Coefficient ($cm^2\ sec^{-1}$)	$L/\sqrt{2Dt}$
1	10^{-2}	1414
10^2	10^{-2}	141
10^4	10^{-2}	14.1
10^6	10^{-2}	1.4
1	1.0	141
10^2	1.0	14.1
10^4	1.0	1.4
10^6	1.0	.14.
1	10^2	14.1
10^2	10^2	1.4
10^4	10^2	.14
10^6	10^2	.014

A diffusion coefficient of 10^2 would correspond to a step size of 0.1 cm at 10^4 cps or to 1 cm at 100 cps. Both of these combinations are unlikely and therefore a value of $D = 10^2$ is unlikely. The value of P can become very small for $L/\sqrt{2Dt} >> 1$. The number of viable organisms moving to the lander is, however, approximately the product of P and the number of viable organisms on the bus surface. The quantity P can be very small but the product can be of appreciable size. When $x_0/\sqrt{2Dt}$ is large the integral can be expressed as follows:

$$(2\pi)^{-1/2}\int_{y_0}^{y_1} e^{-\lambda^2/2}\,d\lambda = \frac{1}{2}\left[\operatorname{erf}\frac{y_1}{\sqrt{2}} - \operatorname{erf}\frac{y_0}{\sqrt{2}}\right]$$

$$\cong (2\pi)^{-1/2}\left[\frac{e^{-y_0^2/2}}{y_0} - \frac{e^{-y_1^2/2}}{y_1}\right], \quad \begin{array}{l} y_0 >> 1 \\ y_1 >> 1 \end{array} \tag{5-4}$$

Consider the case where $D = 1\ \text{cm}^2\ \text{sec}^{-1}$ (0.1 cm steps at 100 cps) and the total number of viable organisms on the lander is T. We take the value of x_0 as a characteristic length of the bus (say 200 cm) and $x_1 - x_0$ as a characteristic length of the lander (say 200 cm). The number of viable organisms expected to reach the lander in time t is given approximately by

$$N = TP = \frac{T}{200}\sqrt{\frac{t}{\pi}}\left[e^{-141/\sqrt{t}} - \frac{1}{2}e^{-282/\sqrt{t}}\right], \quad t < 10^4 \text{ sec} \tag{5-5}$$

If $t = 100$ sec, $P \cong 2\times10^{-8}$ requiring that T be of the order of 10^8 before recontamination can occur in a period of 100 sec.

A one-dimensional diffusion process is sufficient for our purposes here, although a more detailed investigation should include the influence of diffusion in directions which do not bring particles into contact with the lander.

An important condition which can not be taken into account now is the roughness of the surface over which the particles are moving. It is expected that this can only be investigated by an experimental program.

5.4 EFFECT OF METEOROIDS AND DUST

Meteoroids and dust have two principal effects on the recontamination processes. Impacts of these particles can kill biological material on the surface of the bus during the time previous to biobarrier removal. They can also contribute material to the cloud around the spacecraft which may be acted upon by other forces to move it to the lander. In the case where material is kicked off it may remain viable. If the biological material is originally within the dimensions of the crater formed by the high-speed particle it will probably be killed. The magnitude of the kick-off effects can be estimated using the data obtained from Mariner IV (Ref. 6). There were 215 impacts during the mission with impulse above about 6×10^{-5} dyne sec on an area of 3.5×10^{-2} m^2. The size of these incoming particles varied from 1 to 100 microns in diameter. To estimate the number of particles kicked off, we assume that the area of the crater lip is the same order of magnitude as the area of the incoming particle. If the particle is 100 microns in diameter the total area over which particles will be kicked off is $215\left[\frac{100(10^{-6})}{2}\right]^2\pi = 1.7\times10^{-6}$ m^2 on the Mariner IV area of 3.5×10^{-2} m^2. This is about 5×10^{-5} of the area exposed. If there are about 10^5 viable organisms per ft^2 and a total area of about 3000 ft^2, then about 1.5×10^4 viable organisms will be kicked off. Only a small fraction of these will remain in the cloud and be available to move to the lander.

5.5 ORBIT INSERTION AND TRIM MOTOR BURN

Material in the nozzle boundary layer may be turned back in a direction opposite to the main flow of the jets. It may enter the cloud around the spacecraft or it may attach to the surface of the vehicle and move to the lander by the diffusion mechanism discussed in Part 5.3. To estimate the fractional part of the nozzle gas which flows in the boundary layer of either the orbit insertion or the trim motor, assume that the boundary layer is approximately one percent of the running length of the nozzle. The mass flow rate in the boundary layer is given by the expression

$$\dot{M}_{BL} = \rho_{BL}(0.01\ell)\, v_{BL}\, C \tag{5-6}$$

where

ρ_{BL} = average density in the nozzle boundary layer at the exit plane

ℓ = nozzle running length

v_{BL} = average velocity in the boundary layer at the exit plane

C = circumference of the nozzle in the exit plane

The total flow rate is approximately

$$\dot{M}_T = \rho_e A_e v_e \tag{5-7}$$

where

ρ_e = average density of main flow at the exit plane

A_e = area of nozzle at exit plane

v_e = average velocity of main flow at the exit plane

The fractional flow of boundary layer gas is

$$\frac{\dot{M}_{BL}}{\dot{M}_T} = 0.01\,\ell \frac{\rho_{BL}}{\rho_e}\,\frac{C}{A_e}\,\frac{v_{BL}}{v_e} \tag{5-8}$$

Since the boundary layer gas has a lower temperature and is at the same pressure as the main flow, its density will be higher, probably by about a factor of two. The ratio C/A_e is equal to $2/r$, where r is the radius of the nozzle at the exit plane. The average boundary layer gas velocity is lower, by about a factor of four. The fractional flow will then be given approximately by

$$\frac{\dot{M}_{BL}}{\dot{M}_T} = 0.01\, \ell/r \tag{5-9}$$

The quantity ℓ/r will be about 1.5 to 3 so that about 1.5 to 3 percent of the propellant can flow in the boundary layer. This estimate is sufficiently accurate for the purpose here, but can be greatly improved by more thorough analysis. The major part of this flow can impact the space vehicle or a smaller part can enter the cloud around the vehicle.

5.6 EFFECT OF PRESSURIZED GAS IN BIOBARRIER

At the moment of initial separation of the biobarrier from the remainder of the vehicle there is the possibility that pressurized gas around the lander can cause recontamination. As the gas leaves the container at the separation point its density may remain sufficiently high to set up a turbulent, chaotic flow which may have the effect of entraining the material in the cloud around the vehicle and causing it to attach to the lander. Similar flow configurations could cause a sweeping of the unsterile surfaces of the bus near the separation plane and move material to the lander. It is recommended that the gas be vented before the biobarrier is opened.

SECTION 6

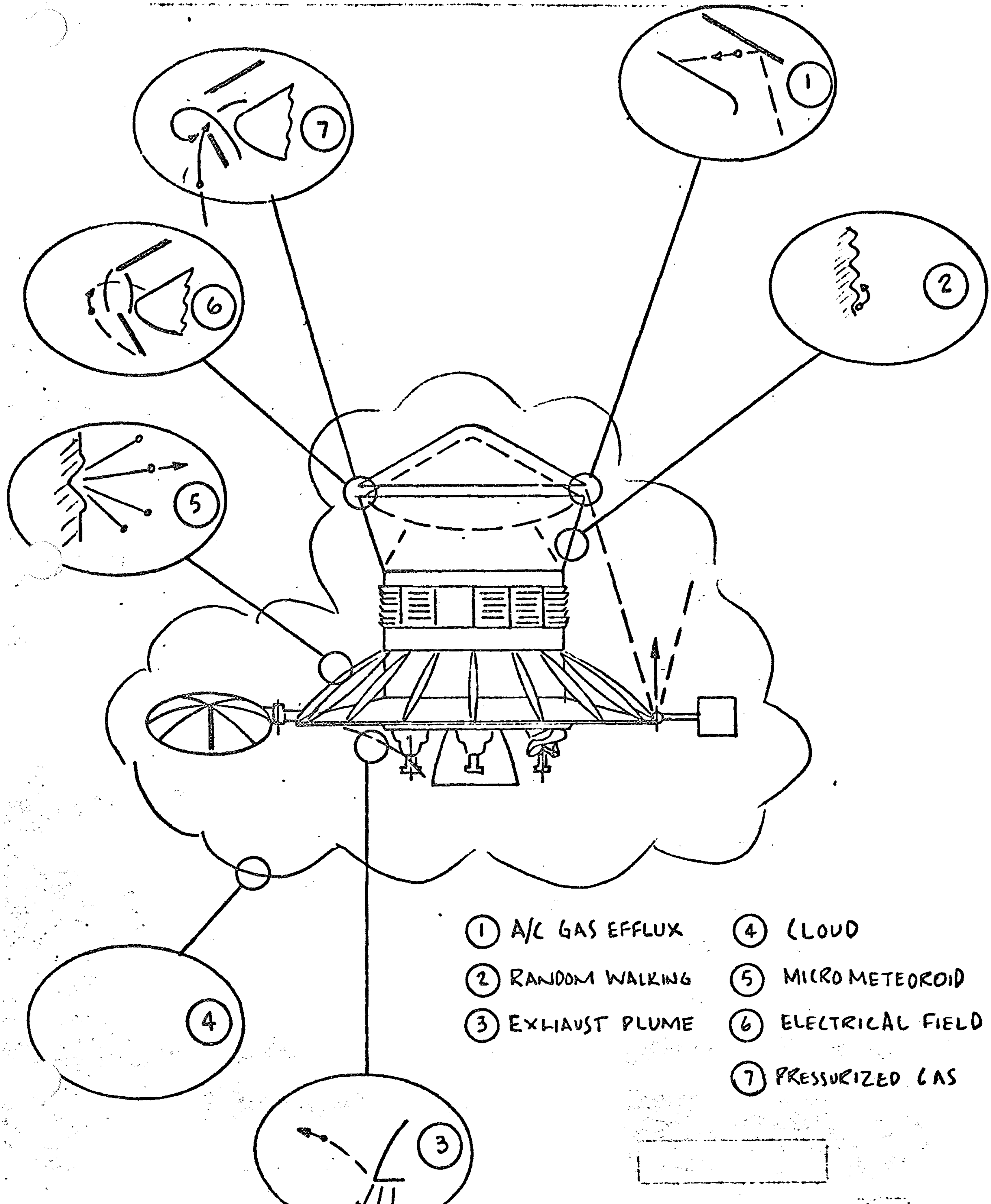
DISCUSSION OF THE PROBABILITY OF RECONTAMINATION OF LANDER

Each of the mechanisms considered in this report contributes to the probability of recontamination of the lander. It is recognized that the estimates made here are first-order calculations and can only serve to indicate the approximate relative magnitude of the different effects in moving viable material to the lander. It is not possible at the present time to derive the probability distribution of the number of viable organisms on the lander at the time it enters the atmosphere of Mars after a given separation sequence. A possible approach to the determination of this distribution is to perform more refined estimates of the effect of each mechanism and combine these probabilistically. Some will be event-connected; that is, the movement of material will occur over a very short period of time. Others will be continuous in time and will depend on the period of time the lander is unprotected. At this time the biological burden on and in the spacecraft is not known and it is not possible to carry out the calculations. It is possible, however, to rank the importance of the effects in an approximate way.

Although the evaporative effects considered in Section 4 are not expected to cause recontamination directly, they result in sufficiently large forces (compared to electrical forces, for example) to place them first in the ranking. Next in order of importance are the electrical forces which may occur if the separating bodies become oppositely charged. If the bodies do not become oppositely charged there is no reason to believe that electrical effects play a significant role in the recontamination of the lander. The attitude control gas jets are next in importance if there are line-of-sight paths from the nozzles to the lander which include reflection from the biobarrier during separation. If reflection is not possible, the effect of the attitude control gas jets is of considerably less importance because it is not likely that the gases will be turned around corners of surfaces on the bus. If the gas itself does not turn it is not possible for macroscopic particles carrying viable organisms to be turned and move to the lander. The effect of dust, based on Mariner IV data, is to introduce material into the cloud around the spacecraft by a kick-off mechanism. This can result in release into space of about 10^{-5} of the average number of viable organisms on the surface during the flight. The effect of burning of the orbit insertion and trim motors is to introduce material onto the spacecraft or into the cloud around it. It is estimated that about one percent of the propellant can move opposite to the main flow. Of least importance is the effect of turbulent flow of any gas which is used as a pressurizing gas within the biobarrier.

In Figure 6-1 several potentially important recontamination mechanisms are illustrated.

Figure 6-1. Illustrating Several Potentially Important Lander Recontamination Mechanisms.



SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 RESULTS AND CONCLUSIONS

1. The order of importance of the effects considered in this report is as follows:

    Evaporative streaming

    Electrical forces at separation of biobarrier and lander

    Attitude control gas, particularly reflection from the inside of the biobarrier in conjunction with biobarrier removal

    Random walk of macroscopic particles carrying viable organisms over the spacecraft surface (due to spacecraft vibration)

    Meteoroid effects (kick-off)

    Attitude control gas: turning of macroscopic particles around surface edges

    Orbit insertion and trim motor burning causing particles to move opposite to the main flow

    Pressurized gas in the biobarrier

2. The study has shown that the requirement of no line-of-sight path from the lander to any unsterile part of the spacecraft should include, as well, that no reflections from the biobarrier can result in line-of-sight paths. This favors a biobarrier which opens and shields the lander from the bus.

3. Atomic and molecular clouds of material evaporated from the surfaces of the lander are an important environmental factor in the assessment of the ability of macroscopic particles to attach to the lander.

4. Electrical forces are most important as a recontamination mechanism during the early phases of separation of the biobarrier and of the lander.

5. No electrical mechanism has been identified which acts to contaminate the lander during the period from after biobarrier separation until the lander begins to separate.

6. Asymmetrical removal of the biobarrier and the simultaneous firing of an attitude control gas jet (which the tip-off torque causes) is an importan potential recontamination mechanism.

7. Based on preliminary information, after the biobarrier is opened the turning of macroscopic material in jet plumes around surface edges will not occur after the flow moves about ten nozzle-exit diameters from the nozzle.

8. Movement of material over the surface of the spacecraft in which macroscopic particles leave and return to the surface will be influenced by the evaporative effect of surface materials with high vapor pressure or high rates of decomposition.

9. The effect of meteoroids is to reduce the number of viable organisms on the surface and to introduce some of them into the cloud of particles around the spacecraft.

10. Most of the material in the boundary layer and a very small amount of material in the free-stream flow of the orbit insertion and trim motors can move in the direction opposite to the main flow and impinge on the spacecraft. Because of the low density of this flow it will be unlikely to turn macroscopic particles around a surface to contact the lander.

11. Pressurized gas within the biobarrier can, at the moment of biobarrier separation, be a potential recontamination mechanism.

7.2 RECOMMENDATIONS

1. No line-of-sight paths, including reflection from the sterile inner part of the biobarrier during its separation, should be allowed from any unsterile part of the bus to the lander.

2. Further study of the effect of evaporative streaming from materials to inhibit attachment of macroscopic particles to the lander should be carried out. This should include an evaluation of the utility and practicality of purposely introducing material on the lander or inside the biobarrier to enhance the streaming of atoms or molecules away from the lander.

3. A study of the ability of jets in the space environment to turn macroscopic particles around surface edges should be carried out to confirm the preliminary conclusion that this does not occur.

4. A study of the flow of boundary layer material from the orbit insertion and trim motors in a direction opposite to the main flow should be conducted.

5. If pressurized gas within the biobarrier is a requirement it should be vented before separation of the biobarrier occurs.

6. A system analysis of the recontamination probability of each candidate separation sequence should be carried out after more definitive analysis has established the probability distribution of recontamination caused by each mechanism within a sequence.

SECTION 8 - APPENDIX

BASIC DATA ON ATOMIC AND MOLECULAR CLOUDS AROUND SPACECRAFT

9.1 EVAPORATIVE RATES OF INORGANIC ELEMENTS

There is considerable data and reasonably accurate theory available for inorganic evaporative rates based on Langmuir's (Ref. 7) original work. This subject was reviewed recently by Jaffee (Ref. 8) from which much of the data shown here has been taken.

The evaporation or sublimation of the elements can be estimated from the Langmuir equation which can be expressed in three different forms.

$$W = \frac{p_v}{17.14}\sqrt{\frac{M}{T}} \qquad (8\text{-}1)$$

where

W = rate of mass loss $(g/cm^2\ sec)$

p_v = vapor pressure of inorganic material (mm Hg)

T = temperature of outer surface of material $(^\circ K)$

M = molecular weight of material (g)

$$S = 0.059\ \frac{p_v}{\rho}\sqrt{\frac{M}{T}} \qquad (8\text{-}2)$$

where

S = rate of sublimation (cm/sec)

ρ = density of solid material (g/cm^3)

$$\dot{N} = \frac{WN_A}{M} = 3(10^{22})\frac{p}{\sqrt{MT}} \qquad (8\text{-}3)$$

where

$\dot{N}$ = number of molecules leaving (number/cm^2 sec)

N_A = Avagadro's number (6.02×10^{23})

For a Boltzmann distribution the average velocity (nearly the sonic velocity) at which the particles leave the surface is

$$\bar{v} = \sqrt{\frac{8}{\pi} \frac{N_A kT}{M}} \tag{8-4}$$

The approximate average number density of particles around the body under equilibrium conditions for flat plate geometry can be found from

$$\begin{aligned}
\rho_v &= \frac{\dot{N}}{\bar{v}} \\
&= \frac{WN_A}{M} \sqrt{\frac{\pi M}{8N_A kT}} \\
&= W \sqrt{\frac{\pi N_A}{8MkT}} \\
&= 6.16\,(10^{18})\,\frac{P_v}{\sqrt{T}} \quad cm^{-3}
\end{aligned} \tag{8-5}$$

Since p_v increases very rapidly with temperature, the density of the vapor increases with T. It can be easily shown that the vapor density can also be expressed as

$$\rho_v = 1.05\,(10^{18})\, S\rho/\sqrt{M} \tag{8-6}$$

Some typical values of temperatures at which sublimation rates are of a given value are shown in Table 8-1 taken from Reference 9.

Vapor pressure information is given in Figure 9-1.

Table le . Sublimation of metals and semiconductors in high vacuum[a]

Element[b]	Temperature at which sublimation rate is							
	10^{-5} cm/yr (1000 Å/yr)		10^{-3} cm/yr (0.0004 in./yr)		10^{-1} cm/yr (0.040 in./yr)		Melting point	
	°C	°F	°C	°F	°C	°F	°C	°F
Cd	40	100	80	170	120	250	320	610
Se	50	120	80	180	120	240	220	420
Zn	70	160	130	260	180	350	420	790
Mg	110	230	170	340	240	470	650	1200
Te	130	260	180	350	220	430	450	840
Li	150	300	210	410	280	530	180	360
Sb	210	410	270	520	300	570	630	1170
Bi	240	470	320	600	400	750	270	520
Pb	270	510	330	630	430	800	330	620
In	400	760	500	940	610	1130	160	310
Mn	450	840	540	1010	650	1200	1240	2270
Ag	480	890	590	1090	700	1300	960	1760
Sn	550	1020	660	1220	800	1480	230	450
Al	550	1020	680	1260	810	1490	660	1220
Be	620	1140	700	1300	840	1540	1280	2330
Cu	630	1160	760	1400	900	1650	1080	1980
Au	660	1220	800	1480	950	1750	1060	1940
Ge	660	1220	800	1480	950	1750	940	1720
Cr	750	1380	870	1600	1000	1840	1880	3410
Fe	770	1420	900	1650	1050	1920	1540	2800
Si	790	1450	920	1690	1080	1970	1410	2570
Ni	800	1480	940	1720	1090	2000	1450	2650
Pd	810	1490	940	1720	1100	2020	1550	2830
Co	820	1500	960	1760	1100	2020	1500	2720
Ti	920	1690	1070	1960	1250	2280	1670	3040
V	1020	1870	1180	2150	1350	2460	1900	3450
Rh	1140	2080	1330	2420	1540	2800	1970	3570
Pt	1160	2120	1340	2440	1560	2840	1770	3220
B	1230	2240	1420	2580	1640	2980	2030	3700
Zr	1280	2340	1500	2740	1740	3150	1850	3360
Ir	1300	2380	1500	2740	1740	3150	2450	4450
Mo	1380	2520	1630	2960	1900	3450	2610	4730
C[c]	1530	2780	1680	3050	1880	3400	3700	6700
Ta	1780	3250	2050	3700	2300	4200	3000	5400
Re	1820	3300	2050	3700	2300	4200	3200	5800
W	1880	3400	2150	3900	2500	4500	3400	6200

[a]Based on vapor-pressure data of Ref. 10.

[b]Gaseous molecules taken as monatomic, except Se, Te, Sb, Bi taken as diatomi

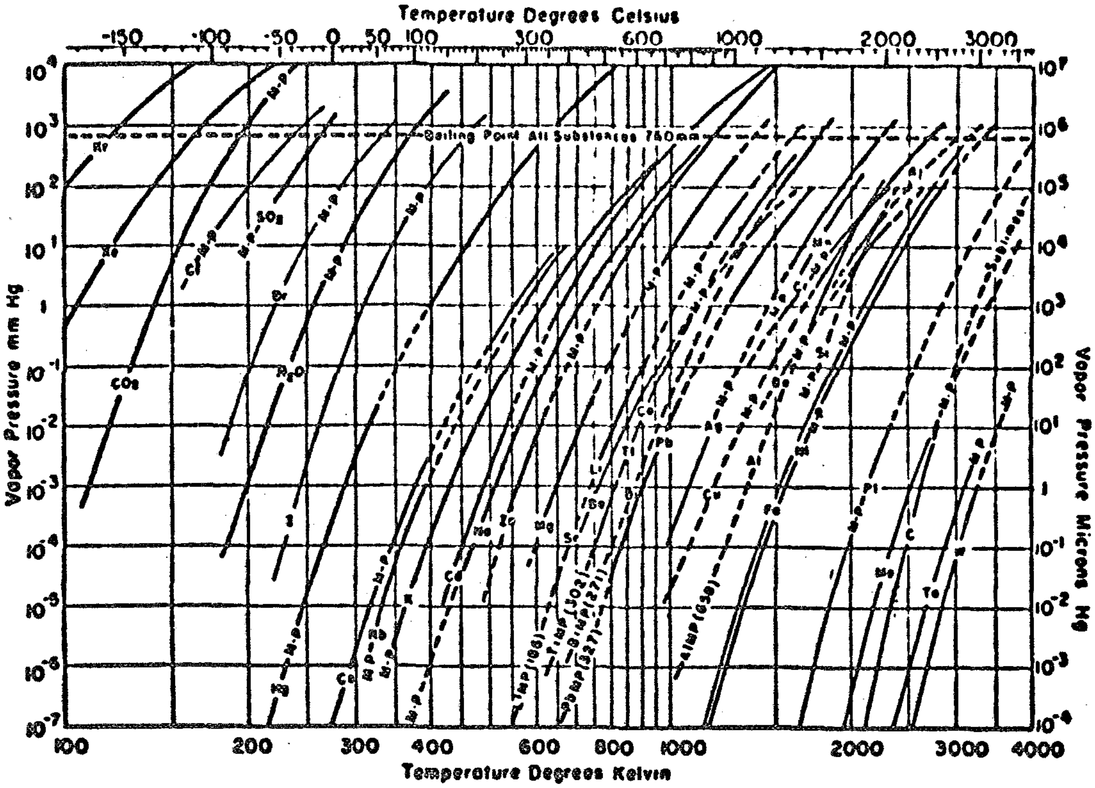


Figure 8-1. Vapor-pressure data.

Some values of vapor density for the flat plate geometry are given in Table 8-2.

Table 8-2. Vapor pressure and density for selected elements.

Element	Temperature (°K)	Vapor Pressure (p_v) (mm Hg)	Vapor Density (ρ_v) (cm^{-3})
Mg (MP 900°K)	1000	10	$1.97(10^{18})$
Mg	490	10^{-7}	$2.79(10^{11})$
Al (MP 658°K)	900	10^{-7}	$2.06(10^{10})$
Al	600	$\sim 10^{-14}$*	$\sim 2(10^{4})$
Al	300	$\sim 10^{-18}$*	~ 2
Ti	580	10^{-7}	3.6×10^{10}
Ti	300	$\sim 10^{-12}$*	$\sim 3 \times 10^{5}$
Cs	300	2×10^{-6}	7.2×10^{11}
Fe (MP 2000°K)	1500	8×10^{-4}	$1.28(10^{15})$
W (MP 3700°K)	2600	10^{-7}	$1.2(10^{10})$
Zn	300	10^{-11}*	$\sim 2 \times 10^{7}$

*Estimated from extrapolated vapor pressure data.

The value of vapor density depends sensitively on the temperature; e.g., a doubling of the temperature of Magnesium increases the vapor density by seven orders of magnitude.

8.2 EVAPORATION RATES OF INORGANIC COMPONENTS

The rate of evaporation of inorganic compounds is more complex because loss of material can occur by several mechanisms. The Langmuir equation is appropriate for the sublimation mechanism if vapor pressure data is available. The compounds can undergo decomposition in which one of the products is volatile. This is potentially important because many of the bodies are coated with protective layers or layers to adjust emissivity and solar absorptivity. These compounds could be organic however (see below). The usual approach is to find from free energy values of the reaction the value of the equilibrium constant, K. For example, in the reaction

$$M_0S_2(s) \rightarrow M_0(s) + S_2(g)$$

$$K = p_{S_2} \qquad (8\text{-}7)$$

If K is known, the decomposition pressure can be computed and used in the Langmuir equation to find loss rate. In the example above, the rate of loss of material is 10^6 times greater than it would be if decomposition did not occur. This must not be considered a typical case, however. Some examples are given in Table 9-3.

The vapor (number) density for this set of inorganic compounds is higher than that for the metals at equivalent temperatures.

Table 8-3. Sublimation of some inorganic compounds in high vacuum

	Temperature and vapor density* when sublimation rate is:						
	10^{-5} cm/yr (1000 Å/yr)		10^{-3} cm/yr (0.4 mils/yr)		10^{-1} cm/yr (40 mils/yr)		Melting Point °C
Compound	T(°C)	$\rho_v(cm^{-3})$	T(°C)	$\rho_v(cm^{-3})$	T(°C)	$\rho_v(cm^{-3})$	
CsI	120	$9.4(10^6)$	160	$9.4(10^8)$	240	$9.4(10^{10})$	620
MgO	540	$1.8(10^7)$	730	$1.8(10^9)$	1090	$1.8(10^{11})$	2800
MoS_2	730	$1.5(10^7)$	960	$1.5(10^9)$	1480	$1.5(10^{11})$	--
ZrO_2	1070	$1.6(10^7)$	1320	$1.6(10^9)$	1480	$1.6(10^{11})$	2700
BeO	1340	$1.9(10^7)$	1480	$1.9(10^9)$	1700	$1.9(10^{11})$	2550
ThO_2	1400	$2.0(10^7)$	1600	$2.0(10^9)$	1900	$2.0(10^{11})$	3300

*Assuming no decomposition; actual value may be two to three times higher if decomposition occurs as in the case of MoS_2 where ρ_v will be twice as large.

9.3 ORGANIC COMPOUNDS

Some organic compounds will obey the Langmuir equations. This is particularly true of the lower molecular weight oils. Compounds such as teflon and phenolic degrade by breaking into fragments of variable molecular weight. The equilibrium decomposition pressure is not known for many of the polymeric compounds. For these reasons the higher molecular weight molecules will not obey the Langmuir equation and empirical weight loss information must be used. Long-chain polymeric compounds lose material from within as we l as from the surface. At least up to thicknesses of one or two millimeters the decomposition takes place throughout the sample and experimental results are presented in terms of percent weight loss. Some data on decomposition rate is shown in Table 8-4 (Ref. 8).

Table 8-4. Decomposition of polymers in high vacuum

Polymer	Temperature for 10% Weight Loss in Vacuum (°C) Per Year
Nylon	30 - 210
Epoxy	40 - 240
Urethane	70 - 150
Vinyl butyral	80
Vinyl chloride	90
Linseed oil	90
Neoprene (chloroprene)	90
Methyl methacrylate	100 - 200
Butyl rubber	120
Styrene	130 - 220
Phenolic	130 - 270
Cellulose acetate	190
Propylene	190 - 240
Natural rubber	190
Isaprene	190
Melamine	190
Mylar, dacron	200
Polyethylene (low density)	240 - 280
Butadiene	250
Polyethylene (high density)	290
Tetrafluoroethylene (teflon)	380
Methyl phenyl silicone resin	>380

In the case of phenolic which degrades to C_5H_5O a 10-percent weight loss per year of a 1-mm thick sample at about 300°K would give a vapor number density of the monomer of approximately

$$\rho_v = 3\times10^{9}\ \text{cm}^{-3} \tag{8-8}$$

obtained from

$$\rho_v = \frac{0.1\rho N_A}{M v_v N} \tag{8-9}$$

where

ρ = density of solid material (g cm^{-3})

N_A = Avagadro's number

M = molecular weight of monomer (= 83)

$\bar{v}_v$ = average velocity of vapor ($\sim 10^4$ cm/sec)

N = number of seconds/year ($3.15(10^7)$)

and also

$$\bar{v}_v = \sqrt{\frac{\pi N_A kT}{8M}} \tag{8-10}$$

9.4 SPUTTERING OF SURFACES

The amount of surface sputtering will depend on the kind of surface, but order-of-magnitude estimates can be made of the rate at which particles will be removed from the surface. The spacecraft will strike about 10^{16} atoms/cm^2 sec at an energy of 4 to 5 ev (Ref. 9). Sputtering efficiency is not well known but are of the order of 10^{-10}; thus about 10^6 atoms/cm^2 sec would be removed from the surface. This amount of material, or even several orders of magnitude increase, would not contribute significantly to the vapor density already found from sublimation or decomposition.

9.5 PHOTOELECTRIC EFFECT DUE TO SOLAR SOURCE

An integration over the solar spectrum quantum yield product at the earth's orbit indicates that an upper limit to the photoelectric emission current density is about 10^9 electrons/cm^2 sec (Ref. 11). The electrons will leave the body with about an electron volt's energy and have a velocity on the order of

10^5 cm/sec. The maximum concentration of electrons due to this effect will be about $10^9/10^5 = 10^4$ electrons/cm^3. This is probably a maximum value because the charge on the body will normally be negative 1 to 10 volts due to differential collision of ions and electrons. Photoelectrons will fall through this potential in one or two Debye lengths and be accelerated to several electron volts, increasing further their velocity and reducing their concentration.

9.6 DEGASSING OF MATERIALS

Metals are known to contain dissolved gases, absorbed layers, pockets of gas within interstitials, and compounds composed of the metals and dissolved gas. The rate of evolution is not well known, although some data is available on the total amount released on outgassing at high temperatures (Ref. 12). The following table includes some information on the rate of outgassing of metals.

Table 8-5. Outgassing rate of several metals.

Metal	cm^3 of gas at S. T. P. per cm^3 of metal
Aluminum	0.1 to 0.5
Copper	0.04 to 0.7
Iron	0.09 to 0.9
Nickel	0.4 to 40
Steel (1% C)	150 to 200

To find an upper limit for the vapor density due to outgassing consider steel to outgas at a uniform rate over a 10-minute period from a 0.1-cm thick layer of material considering the gas to be molecular hydrogen. The amount of material released is taken as 200 cm^3 per cm^3 of steel. The number of moles in 200 cm^3 is 0.2/22.4 = .00894 and the number of molecules is about 5×10^{21}. If these outgas in five days and their velocity is about 10^5 cm/sec, a vapor number density of 10^{11} cm^{-3} could occur. This is an upper limit since a high temperature is required to bake out materials in a few days and steel (used as an example here) is particularly high in outgassed material content. It would appear that this mechanism of obtaining a cloud of material around the body is less important than evaporation or decomposition.

SECTION 9

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